CONFERENCE PROCEEDINGS

Lateral Extents of Permeability Units: Implications for CO_2 Sequestration at the West Pearl Queen Field, Southeastern New Mexico

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ABSTRACT

Outcrop and subsurface data were analyzed to asses the continuity of reservoir sandstones and potential influence on anomalies observed during the CO_2 sequestration phase at the West Pearl Queen Field.

Outcrop exposures indicate the Shattuck Member sandstones of the Queen Formation where deposited in eolian and eolian-influenced shallow lagoons. Although extensive tabular bedding of homogeneous sandstones is observed, heterogeneities such as facies changes, local bedding thickenings, intraclast conglomerates, channels, and thrust fault are also present. These heterogeneities would interrupt uniform injection of CO_2. Estimated average lateral extent of reservoir units from the outcrop data are on the order of 1500 ft (457 m) and are compatible with subsurface data indicating only half of the sandstones extend laterally for more than 1500-1700 ft (457-518 m). Sandy zones interpreted from the well logs and core are also more extensive than their individual component beds and fluid communication within and between zones is limited by low-porosity, fine grained and well-cemented interbeds.

The sandstone reservoirs at the West Pearl Queen Field only superficially appear to correlate between wells as uniform, vertically-stacked layers of laterally-extensive sandstone. This work shows these sandstones are not contiguous between wells except at the closest well spacings. The lack of sandstone continuity and intraformational heterogeneities can explain four anomalies that were observed during CO_2 injection. Specifically the 1) higher than expected injection pressures, 2) resultant lower than expected CO_2 injection rates, 3) apparent localization of the injected CO_2 at the base of the injection well and 4) inordinately long time (three-years) for break-through of the CO_2 into the observation well, located only ¼ mile east of the injection well.

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INTRODUCTION

The West Pearl Queen is a depleted oil reservoir that has produced approximately 250,000 bbl of oil since 1984. Production had slowed prior to CO_2 injection but no previous secondary or tertiary recovery methods had been applied (Pawar, et al., 2006). The initial project involved characterization and field response to injection of CO_2; the field experiment consisted of injection, soak and venting (Pawar, 2006). For 50 days (December 20, 2002 to February 11, 2003) 2090 tons of CO_2 were injected into the Shattuck Sandstone Member of the Queen Formation at the West Pearl Queen site. The injection rate was 40 tons per day; significantly lower than the 100 tons/day expected from preinjection characterization. Early during injection the surface injection pressure reached 1400 psi and thus the calculated bottom-hole constraint of 2900 psi. This pressure was kept constant for the remainder of the experiment. At the end the injection phase the injection well was shut-in and the CO_2 soaked for 6 months. Before venting a post injection 3-D seismic survey was acquired. The injection well was then connected to a separator and allowed to vent. The well flowed freely for 9 days after which it stopped flowing and a pump was installed. After 3 months only 17% of the total injected CO_2 was recovered, 43% recovered after two years. Pre and post-injection production of oil and water proved to be very similar. It was nearly three years before CO_2 was produced in the nearest production well (data in this introduction from Pawar, et al., 2006).

In light of the experimental responses, such as low CO_2 injection rates, higher than expected injection pressures and a lag in interwell communication, this study was undertaken to further assess the continuity of reservoir sandstones in the West Pearl Queen Field. Both outcrop and subsurface data were utilized, this paper is divided into two sections detailing these two data sets. Ultimately, this work discusses the implications for sequestration of CO_2 at sites with limited reservoir dimensions and internal low-permeability baffles and the potential ways to recognize these heterogeneities through outcrop and subsurface analysis.

This project is a shared effort that includes the following organizations Sandia National Laboratories, Los Alamos National Laboratories, Strata Production Company, the New Mexico Institute of Mining and Technology, and the Colorado School of Mines.

PART I. OUTCROP ASSESSMENT OF THE LATERAL EXTENT OF PERMEABILITY UNITS WITHIN THE SHATTUCK SANDSTONE

The outcrops described here are located approximately 60 miles (96 km) west of the West Pearl Queen field (Figure 1). The outcropping strata are time-equivalent to the subsurface West Pearl Queen reservoirs, and although widely separated, the two suites of strata are located in similar paleogeographic positions a few miles landward of the local Delaware basin shelf margin, and they display similar sedimentary structures. Therefore the depositional environments are probably similar, suggesting that they have similar lateral extents.

METHODS

This study focused on the Queen Sandstone where it crops out in the area of Rocky Arroyo (Figure 2), 15-20 miles (24-32 km) northwest of Carlsbad, NM. Although 60 miles (96 km) distant from the West Pearl Queen Field; these are the closest outcrops of strata that are equivalent to the CO_2 injection reservoirs. Measured sections and photo-mosaics were made of the outcrops, and individual sandstone beds were traced laterally. The distances between the lateral terminations of each bed were measured, noting whether each termination was due to a facies change (i.e., the bed ended naturally, pinching out or transitioning to a different, non-reservoir lithology) or whether it was only an apparent bed termination, caused by to erosion or cover by talus and vegetation.

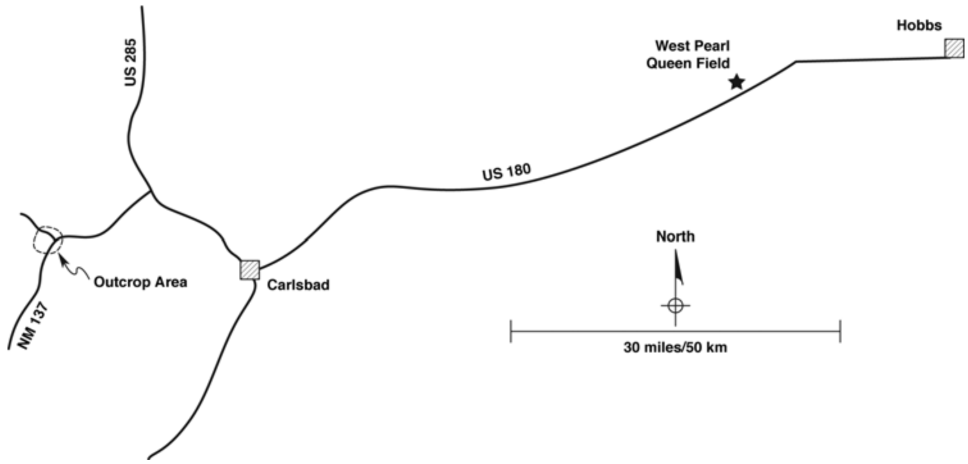

Figure 1: Location map of west Pearl Queen field and outcrops investigated for this paper.

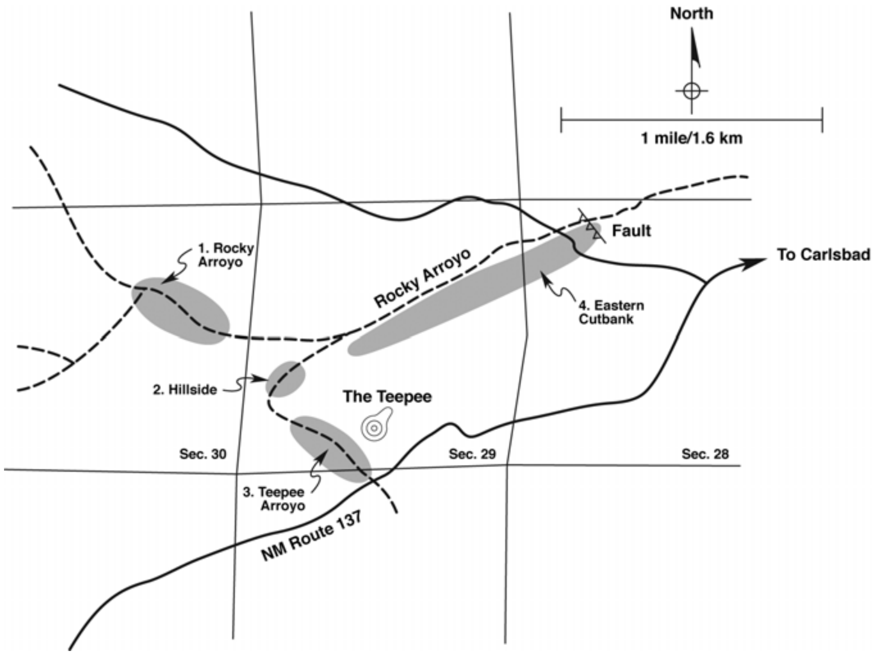

Figure 2: Outcrop location map. Discussions in the text will focus on these four primary outcrop locations (Rocky Arroyo, Hillside, Teepee Arroyo, and Eastern Cutbank).

The recessive, weathered/covered nature of the Shattuck sandstones in outcrop presents a problem when trying to measure the lateral extents of individual beds (Figure 3). Most of the sandstones of the Shattuck proper are cleanly exposed only in road cuts and a few natural outcrops in arroyo cut banks. These outcrops have lateral dimensions of tens to a few hundreds of feet, and are much smaller than the typical lateral dimensions of reservoir-type sandstones. Because of this, the extents of Shattuck-type sandstones in outcrop can only be measured where they are interbedded with thicker dolomites in the upper part of the Queen Dolomite (which underlies the main body of the Shattuck Sandstone). This interbedding protects the sandstones from weathering and overgrowth, allowing them to be exposed over longer horizontal distances where conditions are right.

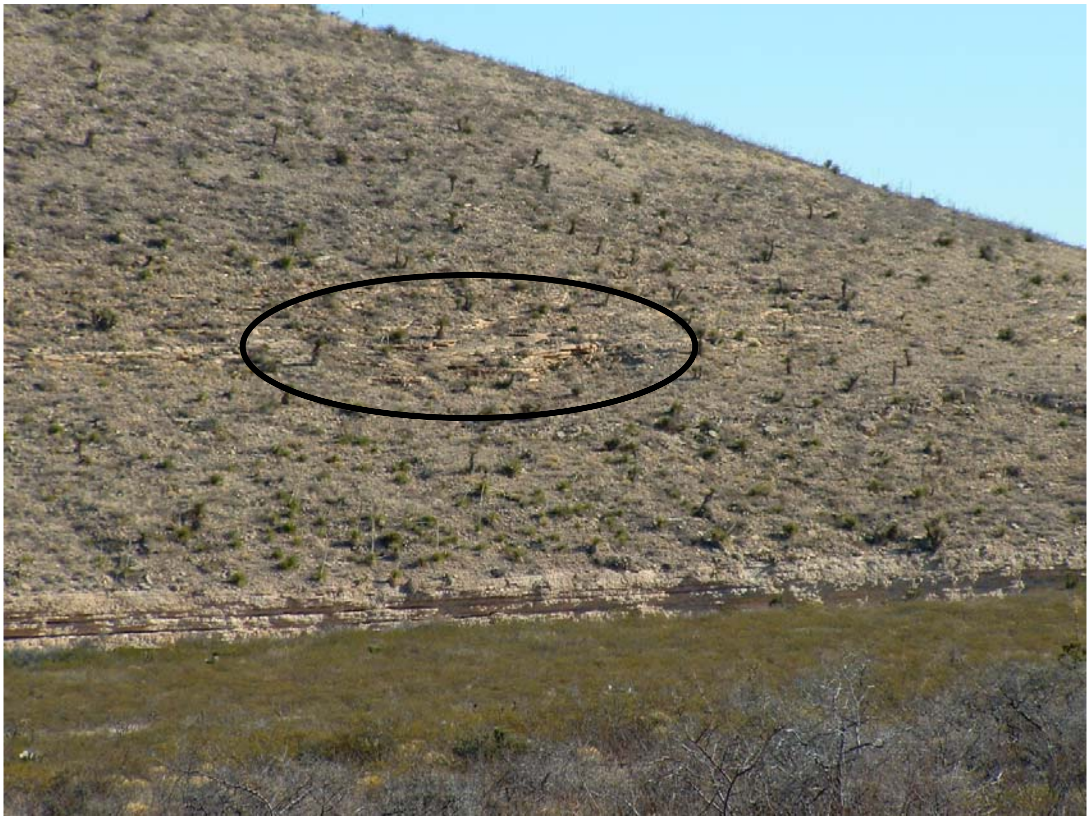

Figure 3: Typical "good" natural exposures of the Shattuck Sandstone Member of the Queen Formation, midway up the hill slope. The better outcrops at the base of the hill are of Queen Dolomite in the bottom of Rocky Arroyo.

However, interbedding with thick dolomite beds suggests that the depositional environments were not entirely analogous to the dominantly sandy, overlying main body of the Shattuck, and in fact the dimensions measurable in these outcrops suggest more laterally restricted units (see below) than indicated by the earlier subsurface study. Nevertheless, thin dolomite beds are also present throughout the main body of the Shattuck, so the difference is one of degree only.

The Shattuck Sandstone interval in outcrop overlies the Queen Dolomite, and underlies carbonates and evaporates of the Seven Rivers Formation. No easily identifiable, laterally extensive sandstone, equivalent to the marker bed that was used to bound the upper limit of the zone of interest in the subsurface, could be identified in the poorly exposed outcrops.

OBSERVATIONS AND INTERPRETATIONS

Sedimentary structures in the Shattuck sandstones that would be diagnostic of depositional environments are poorly defined and difficult to detect because of the uniformly fine-grained nature and mono-mineralic nature of the component sands. Yet enough hints of sedimentary structures are present to suggest that such structures would be common if there were enough heavy minerals or different grain sizes to highlight them. Faint horizontal bedding is the most common feature in the few outcrops where structures are visible (Figure 4), and one instance of parting lineation was noted. Examples of ripple marks (Figure 5a), and small-scale crossbedding (Figure 5b), are present locally, typically on and near the tops of the beds where they suggest reworking of the deposits in shallow-water environments. Local low-angle bedding (Figure 6) and hints of soft-sediment deformation are also present.

Most of these structures suggest deposition in shallow bodies of low-energy water. The one example of parting lineation also suggests shallow, but fast-flowing water. Much of the sand was probably transported to the shallow water environments by winds, some of it as migrating dunes but much of it as dust storms. Low-energy water currents in the lagoons reworked many of the primary eolian deposits, at least their upper parts, into ripples and small crossbeds.

Figure 4: Obscure low-angle to horizontal bedding, highlighted by erosion.

Figure 5a: Small, wave-generated ripple marks on the top of a dolomite bed, indicating a shallow water environment.

Figure 5b: Small cross-beds near the top of a sandstone.

Figure 6: Poorly-defined low-angle cross-bedding (below geologist's right knee and at the left side of the picture, suggest low-angle bedding at the toe of a sand dune.

Most of the Shattuck sandstones occur as beds about a half to two meters (1 ½ to 6 ½ feet) thick. Hints of composite bedding (extensive silty and/or more calcareous zones within the thicker sandstones) suggest that the thicker beds are compound units formed by one or more depositional events, similar to the compound reservoir units seen in the subsurface.

One laterally-extensive contact between a sandstone and the underlying dolomite suggests that the sandstone was deposited in a low-energy, shallow-water setting, and that the dolomite comprised an unconsolidated, muddy substrate at the time of sand deposition (Figures 7, 8). The process that deposited the sand did not rip up the underlying dolomite into an intraclast conglomerate, even though the dolomite mud was soft enough to have oozed into the base of the sand as sand was deposited.

Figure 7: Soft-sediment contact between a dolomite and an overlying sandstone (between the two arrows), suggesting that the sand was gently emplaced over a soupy carbonate substrate. The most plausible environment is a shallow lagoon in which carbonate mud was being precipitated. Sand was blown into the lagoon during dust storms, settling gently and vertically through the water to load into the mud (see following figure for close-up of the contact).

Figure 8: Close-up of the dolomite and the overlying sandstone from the previous photo, showing the irregular but low-energy nature of the contact. High-energy conditions such as fluvial flow would have scoured an irregular contact and ripped the carbonate mud up into imbricated intraclasts, whereas this contact suggests vertical loading by gently deposited sandstone.

A plausible depositional scenario for these sandstones is that sand was blown gently but continuously into the shallow lagoons where dolomite mud had been forming. Wind deposition was prevalent in the Permian environments, with dust storm and sand storm deposits being found in both the marine and nonmarine settings. Sand dunes were probably common, but were rarely preserved. Some of the Shattuck sandstones may in fact record the basal parts of sand dunes that prograded into shallow lagoons, and the thickness of the sandy beds may record the water depths. One channel form, described below, suggests an interesting dichotomy, wherein some high energy process (possibly a storm) cut a channel into existing sandstones, but later low-energy processes (such as wind-blown sand) filled the channel.

All of the sandstones and dolomites in the outcrops described here are extensively fractured. Natural fractures and their potential effects on reservoir permeability are not the focus of this study, but some of the outcrops display excellent pavements that would lend themselves to a detailed fracture study.

LOCAL OUTCROP DATA

1. Rocky Arroyo (south half of the northeast quarter, sec. 30, T. 21 S., R. 24 E.)

Six sandstone beds are exposed at this location (see Figure 2), interbedded within dolomite units of the upper part of the Queen Dolomite in a long cut-bank outcrop on the northern side of Rocky Arroyo as it opens up westward into Indian Basin. The extensive exposure of strata, for about 1500 ft (457 m) along the arroyo, is unique in affording the opportunity to study the dimensions of the sandy units on a scale that is similar to the interwell spacing (500-1900 ft; 152-580 m) at the West Pearl Queen field. The sandstones can be traced laterally because they are interbedded with dolomites (Figure 9), which protect the softer sandstones from weathering and erosion, and because occasional flooding in the arroyo keeps the face of the outcrop clean. The sandstones are not covered by talus and vegetation at this location as they are in most areas where the main body of the Shattuck sandstone comes to the surface (e.g. Figure 3).

The sedimentary structures and scale of bedding in the sandstones are similar to those present in the poorly exposed outcrops above the arroyo where the interbedded dolomites are much thinner and do not protect the easily-weathered sandstones. Because the sedimentary structures are similar, we believe that these sandstones represent similar environments, that they have similar lateral extents, and that they can be used for estimating the lateral extents of sandstone reservoir units where they are not interbedded with thick dolomites in the overlying Shattuck section and in the equivalent subsurface strata.

Four measured sections and a photo-mosaic show that six sandstone beds, varying from one-half to two-and-a-half meters thick, are present in this outcrop. However, effectively there are seven sandstones and fourteen lateral terminations to assess since one unit grades laterally from a sandstone to a sandy dolomite and back again to a sandstone in the middle of the outcrop. Six (43%) of the 14 sand-bed terminations are un-related to depositional changes, being caused by cover and/or erosion, thus some of the measured lateral extents represent only the minimum possible horizontal dimension of the bed. However, the remaining eight known terminations represent a surprisingly large population given the limited extent of the outcrop, and they provide a reasonable basis to begin estimating lateral reservoir dimensions from the outcrop.

Only one of the sandstones can be traced for the entire length of the outcrop, nearly 1400 ft (425 m; Figure 10). Its eastern and western ends are covered; therefore 1400 ft (425 m) is a minimum lateral extent. This bed is a composite bed, composed of three sandstone units separated by two thin, silty, recessive units. Small crossbeds and ripple marks are present in the upper zones of the lower bed in several of the measured sections, suggesting reworking of the top of that bed in shallow-water conditions. The contact with the underlying dolomite is irregular, suggesting that the carbonate substrate was soft and even soupy at the time of sand deposition. Centimeter-scale iron-oxide (probably iron pyrite before weathering) nodules are present a few tens of centimeters above the basal contact, suggesting an interface between anoxic, organic waters related to the buried algal carbonates, and overlying oxygenated waters.

Figure 9: Interbedded sandstones (light orange-brown) and dolomites (light gray) of the upper part of the Queen Dolomite in Rocky Arroyo; both facies are heavily fractured (6-ft geologist for scale).

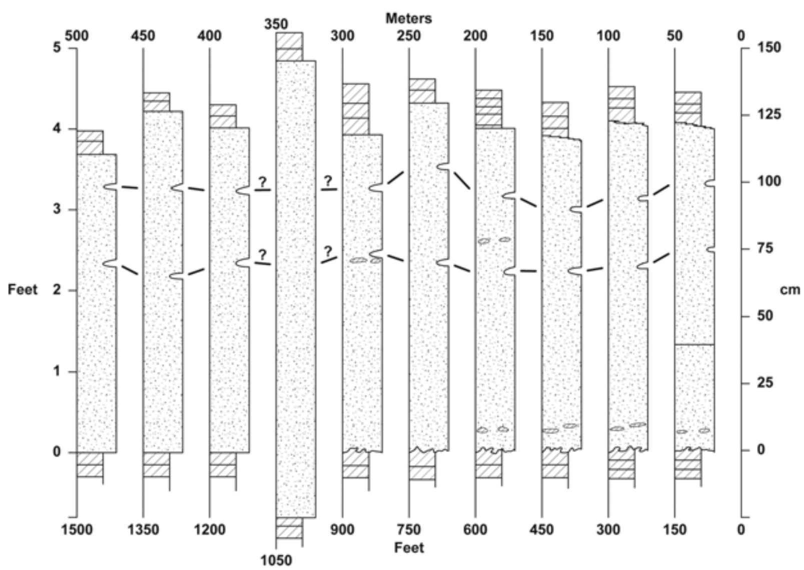

Figure 10: Measured sections through the most continuous bed at Rocky Arroyo. A photograph of the thickened sandstone in the fourth section in from the left can be seen in Figure 11. The thickened area is a cliff face and the location or even presence/absence of the two bedding breaks that are so prominent in the other sections cannot be determined.

Total bed thickness varies only slightly (between 3.9-4.6 ft; 1.2-1.4 m) across its exposed 1400 ft (425 m) extent, with the exception of a local swelling of the bed to approximately 5.6 ft (1.7 m) near the west end of the outcrop (Figures 10, 11). The thickened zone is exposed in a cliff face and could not be studied in detail, but it appears to fill a local depression associated with a facies change in the underlying beds, and its top seems to rise above the local bedding, possibly as a partially preserved dune form. The immediately overlying dolomite beds loose continuity over the top of this swelling, suggesting that water depth changed and that the dolomite was not deposited there.

Figure 11: Thickening of bed at horizon "A-A" above the geologist's head. Another sandstone bed at the level of the geologist's head terminates in a wedge immediately to his left.

Regardless of origin, this thickening represents an anomaly in the homogeneity of the most extensive and uniform of the sandstone beds present in the outcrop. The swelling is not unique: similar features are present in several other of the outcrops studied. The structures are important reservoir heterogeneity considerations.

A second sandstone in this outcrop varies from about 4.9 to 6.5 ft (1.5-2 m) thick. Although it can also be traced as a generally sandy horizon along the entire distance of the outcrop, terminated east and west by erosion, it grades into a sandy dolomite near the middle of the outcrop, thus it represents two separate reservoirs at the same horizon, one present for about 400 ft (122 m) at the west end of the outcrop, the other present at the easternmost 700 ft (213 m). The internal facies change would be a barrier to fluid (CO_2) flow between the two reservoirs.

A thin (half-meter thick) third sandstone extends only 300 ft. (90 m) It occurs several meters stratigraphically below the bed just described and centered below its non-reservoir interval, suggesting a sedimentary relationship. This small bed grades east and west into dolomitic, non-reservoir facies.
A fourth sandstone terminates westward with an abrupt, wedged bedding surface (Figure 11) that may represent the lee slip-face of a dune. This face is onlapped by a dolomite unit. The sandstone can be traced eastward from this contact about 500 ft (152 m) before being obscured by cover. However, it does not appear in the section where it re-appears above the arroyo bed to the east, and thus it probably terminates by facies change to dolomite, and is about 800 ft (245 m) in total lateral extent.

The fifth sandstone, a compound unit of two superimposed beds, is about two and a half meters in total thickness, and is only exposed for 600 ft (183 m) in hollows along the bottom of the arroyo near the east end of the exposure. It terminates east- and westward under cover, but is not present in the section where it resurfaces above a talus zone to the west, so it must terminate by lateral facies change within the talus zone and is probably about 1000 ft (305 m) in minimum lateral extent.

The sixth sandstone is also relatively thick (a doublet of two meter-thick sandstones), but is only exposed for about 300 ft (91 m) at the western end of the exposure, terminating westward behind brush and talus, and eastward under the floor of the arroyo.

TABLE 1: Lateral extents, heights, and terminations of sandstones in Rocky Arroyo

Western termination*	Measured extent (ft)	Eastern termination*	Max thickness (ft)
X	400	Z	4.9
Z	700	X	6.1
X	1400	X	5.6
Z	300	Z	1.6
Z	800	Z	3.3
Z	1000	X	8.0
X	300	X	6.6

X* = covered or eroded end
Z* = known termination by facies change

Ranging from 300 ft (91 m) to at least 1400 ft (427 m; Table 1), the minimum average lateral extent of these seven sandstones is 700 ft (213m). Six, or almost half of the terminations are not facies changes but are unknowns (erosion or covered), and the measured lengths of those beds with unknown terminations are only a minimum, therefore the actual average lateral extent is perhaps twice the minimum average, or on the order of 1500 ft (457 m).

The well-pair correlation data, described in Section II of this paper, suggest that at least half of the composite sandstone reservoirs have lateral dimensions of less than 1700 to 2500 ft (518 to 762 m). Given the limited data, the likely error bars on the data, and the difference that the outcrop beds are interbedded with dolomites at the top of the Queen Dolomite as discussed above, the outcrop and subsurface data sets are compatible.

2. Hillside Sandstone Outcrop (northwest quarter of the southwest quarter, section 29, T. 21 S., R. 24 E.)

The main body of the Shattuck Sandstone is partially exposed in a steep hillside half a mile to the southeast (Figure 12). This hillside, about 60 ft (18 m) high and 250 ft (76 m) wide, is composed predominantly of sandstone. It is stratigraphically higher than the outcrop just described, and equivalent to the sandy lower Shattuck reservoirs at the West Pearl Queen field. The sandstones are again well sorted and very fine grained. However, bedding is thinner, the thick sandstones being composed of tabular beds 10 cm to a meter thick.

Figure 12: Sandy hillside of moderately well exposed Shattuck sandstone. Bedding appears to be uniform but local heterogeneities exist. The arrow marks a block of sandstone float that can be seen in the following photo and used for position reference.

A major permeability discontinuity is present in the hillside, in the form of a 12-ft (3.6 m) thick, 90-ft (27 m) wide sandy unit bounded on the bottom by what appears to be a Permian, syn-sedimentary erosion surface (Figure 13). One plausible interpretation is that it is a channel cut into the tabular beds by a high-energy event, possibly during a storm or flooding. The tabular beds at the margins of the channel have been truncated, and a zone of iron concretions has been cut out, with similar concretions present at the base of the lens, possibly as a winnowed lag deposit. However, incongruously, the channel was subsequently re-filled with the same type of low-energy, thin, tabular sandstones that it was cut into (Figure 14). Wavy, low-angle, and horizontal bedding as well as small ripples are preserved locally, suggesting low-energy depositional conditions, probably eolian deposition during dust storms, reworked by gentle currents. The channel axis is estimated to be northwest-southeast, or roughly normal to the local paleoshoreline.

Figure 13: Right-hand half of the channel form (diagonal contact from upper right to lower left) in the sandy hillside. The upper arrow marks the block of sandstone float used for a position reference between this and the previous photo (Figure 12); the lower arrow shows the position of the following photo.

Figure 14: High-energy, erosional channel-margin contact between low-energy flat-lying sandstones of the substrate on the right and low-energy inclined channel-filling sandstones on the left. A mirror image of this relationship is present on the other side of the channel 100 ft (30 m) to the northeast.

3. Teepee arroyo (southwest quarter, section 29, T. 21 S., R. 24 E.)

The Shattuck sandstone proper is reasonably well exposed, although only in vertical section rather than in wide-scale lateral exposures, in a narrow arroyo that lies just southwest of the conical hilltop of Seven Rivers Formation called "The Teepee" on the local topographic maps. The Shattuck sandstones in this arroyo show a variety of depositional environments, including many of the typical meter-thick, apparently massive sandstones and interbedded thin dolomites. Sedimentary structures such as low-angle crossbeds, small trough crossbedding, rare rippled bedding surfaces, and interbedded dolomites, again suggest low-energy, shallow-water deposition.

Other deposits exposed in this arroyo include a meter-thick intraclast conglomerate (Figure 15). The conglomerate has an irregular base and overlies a deformed shale, suggesting rapid emplacement on top of an unconsolidated bed. The conglomerate is overlain by a horizontally bedded dolomite. The deformed underlying shale and the ripped-up intraclasts indicate a high-energy event, and this is probably a storm deposit, possibly related to the high-energy event that cut the channel in the sandy hillside just described.

Near the top of the arroyo, though well below the evaporitic deposits of the Seven Rivers Formation that overlies the Shattuck Sandstone, another ambiguous sandstone swelling is present. Thickening from 3.3 to 5.2 ft (1.0 to 1.6 m) and then thinning back to 3.3 ft (1.0 m) over a lateral distance of 33 ft (10 m), it overlies a storm-deposit bed of intraclast conglomerate, the top of which is depressed to accommodate about half of the swelling (Figure 16). The rest of the swelling is accommodated by an increase in height of the top of the bed. It is capped by a thin, uniformly thick dolomite. The geometry suggests that the underlying strata were poorly consolidated and bowed down slightly to accommodate the local weight of the sand thickening, and that topographic relief existed on the top of bed at the time that the overlying dolomite was deposited.

Figure 15: Intraclast conglomeratic storm deposit, Teepee arroyo.

Figure 16: Thickened tan-orange sandstone, possibly a drowned, isolated sand dune.

This example and others like it may represent isolated dune forms that were caught by rising sea level as they migrated across a barren shelf, their sharp dune form becoming subdued as they slumped during saturation with water, eventually becoming draped by later deposits. Other fossilized dunes should be present along the same horizon but it cannot be traced out laterally.

4. Eastern cutbank, Rocky Arroyo; (central part, section 29, T. 21 S., R. 24 E.)

The lower valley wall on the south side of Rocky Arroyo cuts straight northeast-southwest across section 29, extending into the northwest corner of section 28. The hillside exposure of Shattuck sandstone described previously (#2; Hillside Sandstone Outcrop) forms the southwestern end of this band of outcrops. The upper part of the Queen Dolomite and the lower part of the Shattuck Sandstone are intermittently exposed in this wall for over a mile, although individual beds cannot be traced laterally since the bedding dip varies, because the interbedded dolomites are too thin to protect the sandstone section from weathering, and because several arroyos interrupt bedding continuity. However, in addition to good fracture pavements (Figure 17) and the normal interbedding of dolomites and well-sorted, fine-grained sandstones, several features are present that affect bedding extent and continuity.

One notable feature is a small thrust fault in the northwest corner of section 28, a hundred yards east of the road that crosses the arroyo. Unmapped on the available geologic maps of the area, the fault plane strikes approximately NW-SE (Figure 18). Vertical displacement is on the order of 15-20 ft (4.6-6.1 m). Breccia zones are present along the fault plane, and also in between bedding planes in the eastern buttressing block where they resemble injections and suggest that the strata may not have been fully lithified at the time of thrusting.

Figure 17: Numerous natural fractures cut a bedding-plane fracture pavement.

Figure 18: Small thrust fault in the Queen Dolomite, Rocky Arroyo.

The thrust fault is located within half a mile of a mapped, arcuate zone of small anticlines, but the orientation of implied compression (NE-SW) is nearly at right angles to the compression suggested by the anticlines (ESE-WNW in this area), and the two are not mechanically compatible and are therefore probably not related. The compression implied by the fault is, however, compatible with compression that would have been derived from faulting along the Huapache Monocline, a deep-seated thrust that strikes NW-SE about three miles to the southwest.

Although the West Pearl Queen Field is not close to a large structure that would be a source of compression, small subsurface faults similar to this thrust fault cannot be ruled out with the available data. In fact, although rare, other, smaller faults (Figure 19) are present elsewhere in the outcrop strata. Faults would be major barriers to fluid flow in a reservoir.

Figure 19: Small thrust fault in Rocky Arroyo. Thinning and thickening of the unit overlying the fault indicate that it formed during deposition.

In addition to subtle structural complexities (variable dip, thrust faulting), sedimentological heterogeneities complicate the reservoir-type strata in the Shattuck sandstones in this area. Another sandy thickening is partially exposed at the base of one outcrop. The bottom of the thickened sandstone is covered below the dry stream bed, but the top of the sandstone has 3 ft (1 m) of relief in the form of two subtle, connected mounds present along the 45 ft (14 m) of lateral exposure of the bed. The layers of sandstone and dolomite that immediately overlie these mounds conform to the double-mound topography, but the successively overlying layers thicken in the troughs and thin over the high points such that bedding 10 ft (3 m) above the mounds is completely flat-lying. The mounds are again inferred to be small drowned sand dunes.

PART I: SUMMARY

The observations on heterogeneities and the measurements of the lateral extents of reservoir-type sandstones in outcrop are compatible with and corroborate the inferences on limited reservoir dimensions made from subsurface data at the West Pearl Queen field to be discussed in the following section. Sandstone outcrops in the area of Rocky Arroyo were deposited in eolian and shallow lagoonal environments. Heterogeneities such as facies changes, local bed thickenings, intraclast conglomerates, channels, and thrust faults interrupt lateral continuity of bedding and would effect the distribution of CO_2. Measured sandstone beds have an average minimum extent of 700 ft (213 m), but actual average extent is likely more, on the order of 1500 ft (457 m). Limited reservoir extents and internal baffles by heterogeneities of the types seen in outcrop may explain the anomalies, such as low CO_2 injection rates, the higher than expected injection pressures, and the observed lag in interwell communication, observed during injection of CO_2 in the West Pearl Queen carbon-dioxide sequestration project.

PART II. WEST PEARL QUEEN FIELD ASSESSMENT OF THE LATERAL EXTENT OF PERMEABILITY UNITS WITHIN THE SHATTUCK SANDSTONE

This study was undertaken in order to assess the continuity of reservoir sandstones of the Shattuck Member of the Queen Formation at the West Pearl Queen field (Figure 20a). Part of this study included an assessment of the depositional environment of the Shattuck sandstones, since sandbodies deposited in marine vs. non-marine environments would be expected to have different lateral extents and reservoir characteristics, and in order to make valid interpretations of the geophysical-log signatures. This environmental study included three cores, although only 20-30% of each core was available for examination due to extensive previous sampling and the absence of depth markings on one core caused some ambiguity. The core study was supplemented by an earlier outcrop study and literature search, and suggests a dominantly non-marine setting, in line with the previously published interpretations (Lorenz pers. com. 2006; Mazzulo et al., 1991, Tait et al., 1962; Hayes and Koogle, 1958).

The Shattuck Sandstone as defined here lies above the Queen Dolomite and below a widespread sandstone marker layer (Figure 20b). This interval is between 64 and 106 ft (19.5 and 32.3 m) thick on the cross sections constructed for the study, thinner to the north and northeast (landward) and thicker to the south where greater subsidence apparently accommodated greater deposition (Figure 21). Lithofacies in the cores suggest that the sandstone reservoirs in the West Pearl Queen area were deposited in saline sandflats ("sabkha"), eolian dunes, and interdune environments (Figure 22). There may also have been some marginal-marine influence, especially in the lowest strata immediately adjacent to the Queen Dolomite and in the higher part of the Shattuck section.

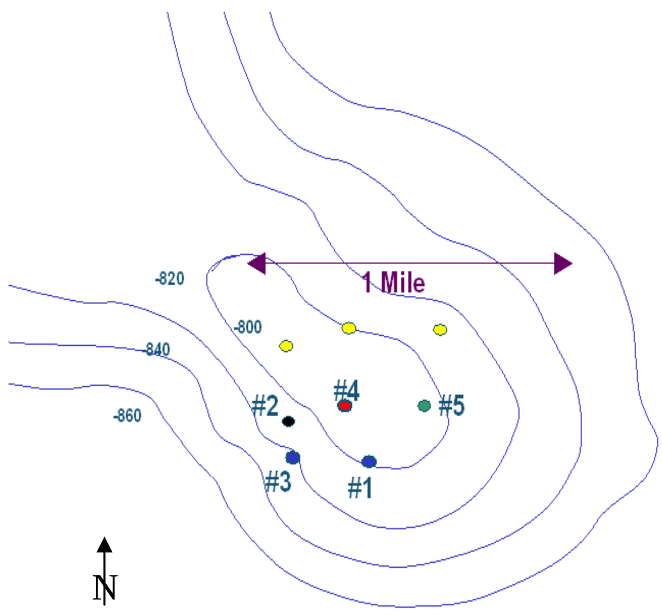

Figure 20a: Structure-Contour map of the West Pearl Queen field, based on well data (compare to the different structure-contour map derived from the seismic data, Figure 9). Colored circles are the wells of different operators in the field; wells #4 and #5 are the injection and observation wells, respectively, and well #1 was cored.

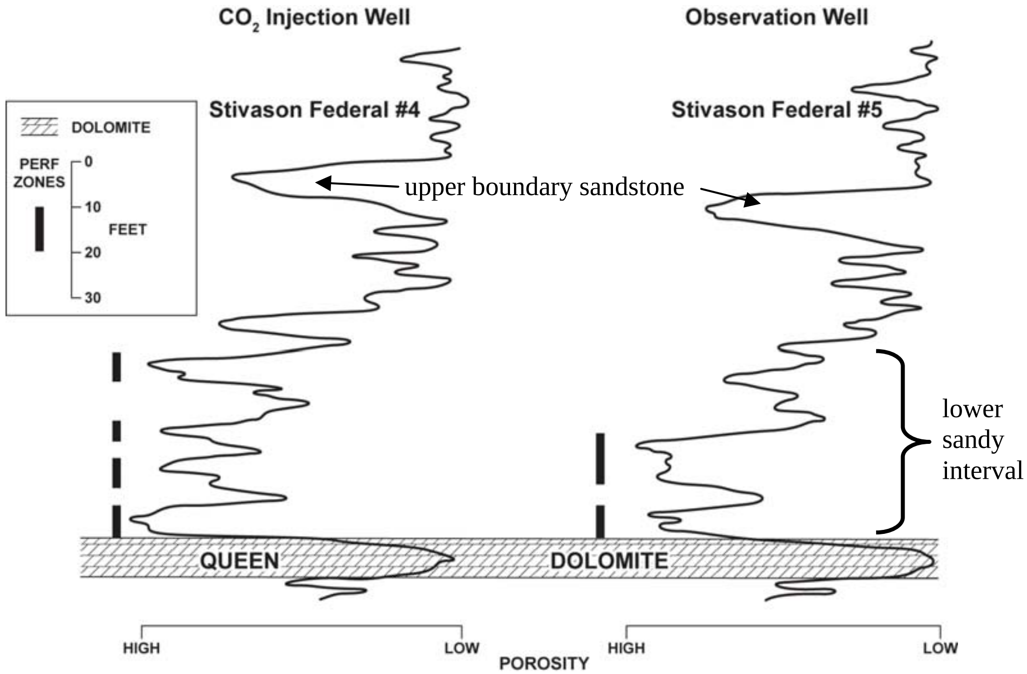

Figure 20b: Neutron porosity log traces for the Stivason Federal #4 (CO_2 injection well) and Stivason Federal #5 (monitoring/observation well). This figure shows the persistent Queen Dolomite bed that anchored the cross sections and well pairs, the laterally extensive sandstone that marks the upper boundary of the study interval, the relatively sandy lower part of the Shattuck interval vs. the finer-grained upper part, the limited zones of perforation in each well, and the thinning of the section in the direction of the Stivason Federal #5 well.

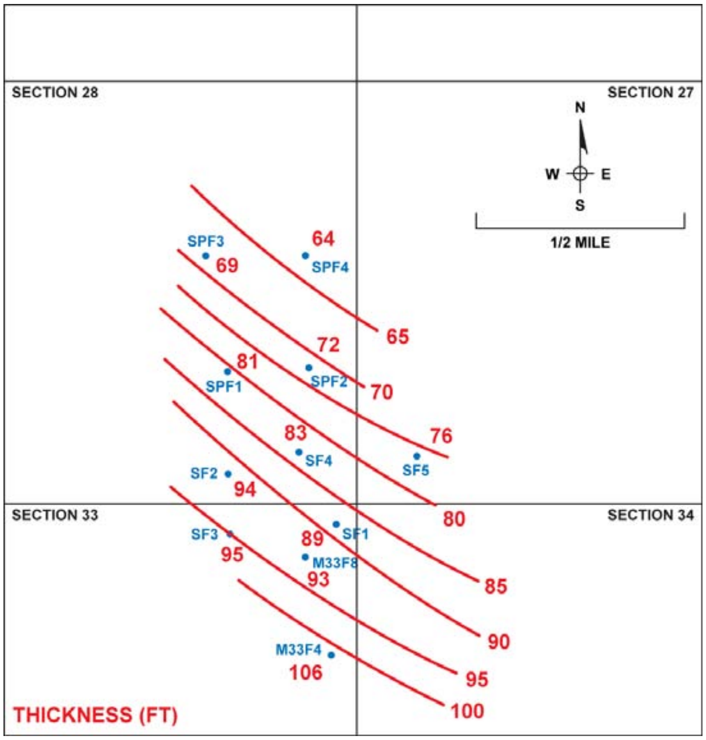

Figure 21: Isopach map of the Shattuck sandstone interval, between the top of the Queen Dolomite and the top of the upper, laterally-extensive, bounding sandstone. The interval thickens to the southwest, down dip, by 42 ft (12.8 m; an added 66%) over the short interval mapped. This thickening had to be accounted for in assessing the probability of bed correlations between wells. Wells SF4 and SF5 in sections 27 and 28 are the injection and observation wells, respectively, near the center of the West Pearl Queen field. Small blue letters are abbreviations of the well names, and red lettering shows the thickness of the Shattuck interval in each well.

High-porosity sandstone beds that form reservoirs capable of accommodating injected CO_2 within the Shattuck interval comprise only 30-40% of the total thickness of the unit, the rest being composed of low-porosity; well-cemented siltstones and local muddy and carbonate intervals. Five such beds and approximately 36 ft (11.0 m; cumulative) of reservoir-potential sandstone thickness are present in the Stivason Federal #4 CO_2-injection well. However, the operator perforated a cumulative of only 22 ft (6.7 m) of vertical height the casing in this well (in the four most promising oil-bearing zones: see Figure 20b), leaving approximately 14 ft (4.3 m) of potential reservoir sandstone behind casing and unavailable for CO_2 storage.

The reservoir sandstones vary from single beds between 2 and 6 ft (0.6 and 1.8 m) thick to compound sandstones up to 16 ft (4.9 m) thick. The lower half of the Shattuck interval has a higher percentage of sandstone, and the compound sandstones in this zone form laterally persistent sandy intervals. The individual beds that comprise these sandy intervals cannot be reliably correlated and probably do not extend between wells. The questions are 1) how well interconnected are the individual beds within the sandy intervals, and 2) what are the likely lateral dimensions of the sandstones and sandy intervals. A lack of lateral reservoir continuity between the wells, especially if combined with a lack of vertical conductivity between the component beds in the sandy zones, would help to explain the injection anomalies.

Figure 22a: Steeply inclined, regular crossbedding of well-sorted, fine-grained sandstone, representing the deposits of an eolian dune environment, as seen in core. One of the bedding planes is highlighted by gray discoloration, suggesting enhanced permeability along this plane. The overlying gray bedding is nearly horizontal and onlaps the inclined dune foresets.

Figure 22b: Evaporitic nodular anhydrite that grew displacively in a fine-grained saline sandflat to sabkha environment.

METHODS

Two approaches, 1) correlations along several cross sections, and 2) correlations between 21 well pairs, were used to semi-quantitatively assess the lateral continuity and extents of the permeability units that control distribution of CO_2 injected into the Shattuck sandstones. The correlations were based in part in the log similarities as described below and in part on knowledge of depositional environments.

Cross Sections

Four cross sections were constructed through the Shattuck interval in the area of the West Pearl Queen field. A three-mile long cross section extends between 11 wells in a generally north-south direction, approximately parallel to the depositional dip. Three shorter, orthogonal cross sections, each extending parallel to the northwest-southeast depositional strike, were also made (Figure 23).

Sections were referenced to the Queen Dolomite, a 6 to 12 ft (1.8 to 3.6 m) thick unit that provides a prominent and easily recognizable marker at the base of the Shattuck Sandstone. This dolomite has a distinctive, low gamma-ray/low porosity geophysical-log signature, and is also prominent outcrop as a highly fractured unit (Figure 24). It was deposited in a wide-spread, shallow, hyper-saline lagoonal setting, and provides a good stratigraphic marker. The subsurface sections were constrained at the top by laterally-extensive, distinctive sandstone that is 5 to 10 ft (1.5 to 3.0 m) thick within an otherwise low-porosity zone.

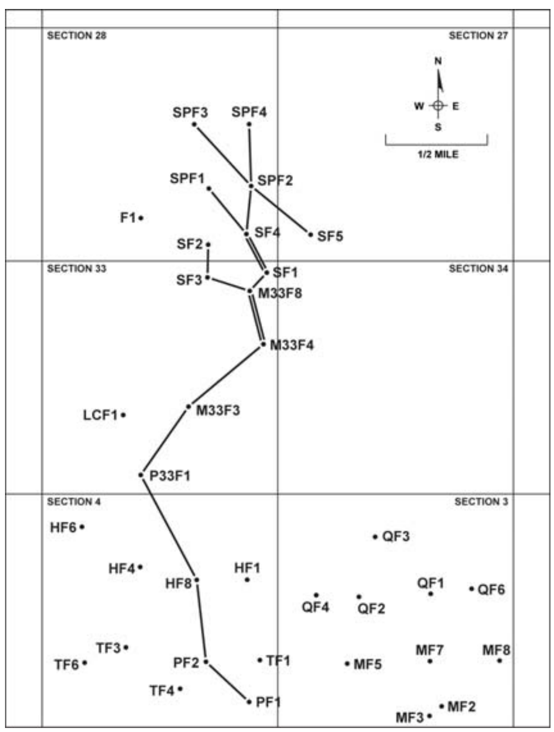

Figure 23: Map showing the lines of the cross-sections constructed for this study. Double lines show where a section is part of both the long, north-south section and one of the oblique sections. Lettering indicates the abbreviations for well names. SF4 and SF5 in sections 27 and 28 are the injection and observation wells, respectively.

Figure 24: Outcrop of the Queen Dolomite, with a yellow, 5" x 7" field notebook for scale. This unit is well bedded and heavily fractured, and forms a persistent layer that is easily recognizable in both outcrop and the subsurface and that can be used as a peg point for assessing correlations of the sandstones in the overlying Shattuck interval. Significant fracturing, if present in the subsurface, could also make this an important potential thief zone.

Gamma-ray logs proved to be useless for correlation purposes because a high potassium feldspar content of the Shattuck sands left little to differentiate the reservoir sandstones from the low-porosity, finer-grained clastic lithologies. However, distinctions between the lithologies were obvious on the density and porosity logs, which delineate the high-porosity units of prime interest for sequestration. An oilfield type of cutoff criterion was used in that only sandstones with more than 12% porosity were considered for correlations.

High-porosity sandstone units were assumed to extend between two adjacent wells if the following correlation criteria were met, listed in order of priority:

1. The position of the high-porosity sandstone is a similar distance vertically from the Queen Dolomite, although allowing for the gradual and regular thickening of the section to the southwest and the related progressively higher position of correlative beds relative to the underlying dolomite marker bed in this direction.
2. The shape of the porosity log profile across the two sandstones in adjacent wells is similar.
3. The possibly correlative sandstones in the wells have at least 12% porosity.

A sandstone that did not correlate between adjacent wells was assumed to pinch out half-way between the wells. The maximum inferred extents of the correlatable sandstones were tabulated and used to determine the maximum, minimum, and average extents along the north-south cross section. The same was not done for the east-west cross sections since they examined only limited distances relative to the maximum sandstone extents observed on the north-south section, which would have provided only an artificially truncated data set.

Well Pairs

The second technique used for assessing the lateral extents of the Shattuck high-porosity sandstones was to make a comparison of correlations of sandstone units between 21 adjacent well pairs, the wells in each pair being separated by distances of between 500 and 1900 ft (152 and 580 m; Figure 25). These correlations also used the Queen Dolomite and the upper, extensive sandstone as the stratigraphic references, and used the same correlation criteria listed above.

The correlation pairs were also examined relative to paleogeography, i.e., by alignment northeast-southwest and northwest-southeast (across and parallel to the depositional strike respectively), as well as north-south and east-west (oblique to depositional strike), in order to see if sandstone continuity varied in these directions.

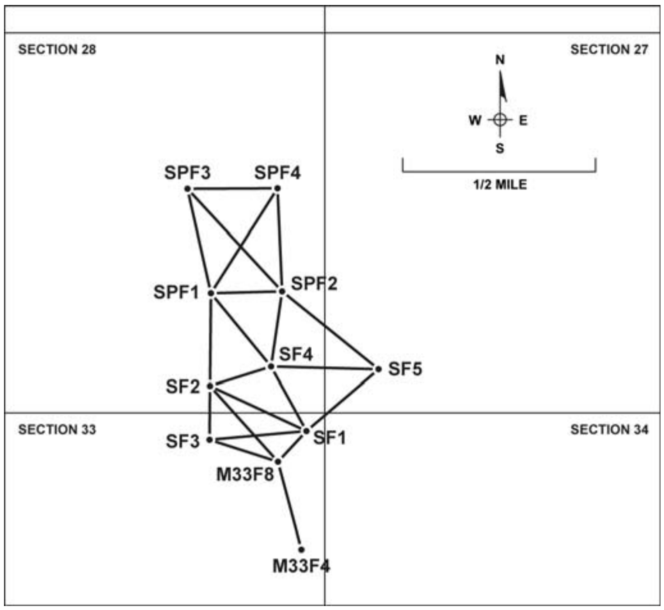

Figure 25: Map showing the well pairs used to derive correlation percentages. Wells SF4 and SF5 near the right center of the figure are the injection and observation wells, respectively, near the middle of the West Pearl Queen Field.

The percentage of total number of reservoir-quality compound sandstone packages in each well pair that appeared to correlate between wells was then plotted against the distance between the well pairs, with the expectation that the interwell correlation percentage would decrease as the distance between wells increases, thus providing a basis for extrapolating the probable lateral extents of typical reservoir units.

Vertical conductivity between individual beds within the compound sandstone packages, and between packages, was assessed by a qualitative examination of the porosity log traces, and corroborated by the existing core-property measurements (porosity and permeability) available for core from the Stivason Federal #1 well.

Caveats

Without evidence such as documented fluid communication between wells or interwell seismic wave guides, it is not possible to say definitively whether similar-looking sandstones penetrated in two adjacent wells at the same depth are actually contiguous between the wells or whether the similarity in depth and log profile are merely coincidental. In future sequestration projects it would valuable to run various tests to assess the interwell connectivity of reservoir units prior to injection.

Some Shattuck sandstone beds can be traced laterally in outcrop for a few thousands of feet, supporting the lateral dimensions derived from the subsurface data below even though the depositional environment of the Shattuck has changed in these more marine deposits exposed northwest of Carlsbad. Nevertheless, the subsurface interwell correlation percentages discussed below do drop off, albeit irregularly, with distance, supporting the inferred correlations.

The longest correlations inferred for this study, up to 2600 ft (792 m), between well pairs and along the north-south cross section, may be spurious, more apparent than real. Beds as little as a foot thick can be resolved in the porosity logs, but these could not be reliably correlated.

CONTINUITY INTERPRETATIONS

Rather than being discrete units that blanket the field in uniform layers, reservoir-quality sandstones in the Shattuck Member of the Queen Formation occur as groups of composite sandstones that form distinct sandy intervals (Figure 7). These intervals in each well are composed of between one and five individual sandstone beds, as inferred from minor inflections of the porosity log traces across the compound units. The sandy intervals typically, though not always, extend laterally between adjacent wells, but in the lower Shattuck interval of interest here, the individual component sandstones commonly do not.

The sandy intervals record widespread conditions and environments that were conducive to local sand deposition. The potential for fluid connectivity within the sandy intervals, between the component sandstone beds, is not well known. As discussed below, the indirect evidence suggests that the potential is not high.

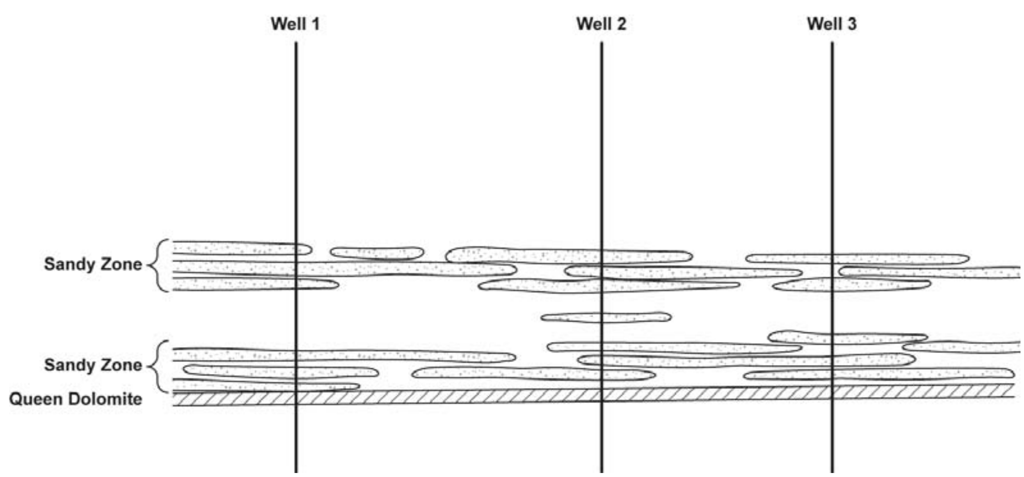

Figure 26: Schematic correlations between wells, showing the interpreted nature of the sandstones in the lower Shattuck interval. The sandstones occur predominantly within sandy intervals that appear to correlate between wells but in fact the component sandstone beds are discontinuous. The individual sandstone beds that comprise the sandy intervals thin and thicken, and commonly pinch out between wells. Locally even the compound sandy intervals themselves terminate and do not correlate.

Lower Shattuck Interval: Cross sections

Between three and six compound sandy packages, varying from 3 to 16 ft (0.9 to 4.9 m) thick, occur within the lower half of the Shattuck interval in the vicinity of the West Pearl Queen field. Core suggests that these sandstones were deposited in eolian dune and interdune intervals when the shelf margin was widely exposed as the sea retreated after deposition of the Queen Dolomite. Sandstones with reservoir potential that were deposited in these environments would not be expected to be as laterally extensive as the equivalent shallow-marine sandstones that can be examined in outcrop 60 miles (96 km) to the east. Dune fields developed above the water table, while briny sabkha environments filled the shallow depressions between dunes and between dune fields. The lower parts of dune deposits were preserved locally by rising water tables, or where a dune was blown into and across a sabkha and became stabilized by the precipitation of evaporitic cementing minerals.

Four of the five high-porosity sandy packages in the Stivason Federal #4 well were perforated in the injection well. The fifth interval apparently did not have promising oil indications on the geophysical logs and was not perforated by the operator when completing the well. Therefore some of the potential Shattuck CO_2-sequestration reservoirs penetrated by the injection well were not accessed during injection.

Twenty-one compound sandstone packages were identified within the north-south cross section. Some of the packages in the lower Shattuck interval were tentatively correlated as far as 9000 ft (2740 m) on the section. The average correlation distance was about 4000 ft (1220 m) and the minimum distance was less than 1000 ft (305 m). The sandy zones fan out and increase in number southward as the Shattuck section thickens: three sandy packages are present in the northern wells, whereas up to five packages are present in the southern wells.

Lower Shattuck Interval: Well Pairs

The graph of sandstone correlation percentage versus interwell distance for different pairs of wells in this lower Shattuck interval (Figure 27a) does not show tightly grouped data from which general trends can easily be extracted, but it does suggest that all or most of the compound sandstone packages extend laterally for at least 1000 ft (305 m).

The percentage of interwell correlations, which can be used as a proxy for the probability of sandstone continuity, starts to drop off at distances greater than 1000 ft (305 m). Although there are still data points suggesting good reservoir continuity at distances up to 1900 ft (580 m) the maximum interwell distance plotted for the well pairs), the data also suggest that 20-30% of the sandy reservoir packages do not extend farther than 1500 ft (457 m). An empirical extrapolation of the trend suggests that only 50% of the sandy packages extend laterally for more than 2500 ft (762 m). This is consistent with the average correlation distance of 4000 ft (1220 m) derived independently from the cross sections.

Although the subsets of data are small when the well pairs are broken down by alignment relative to paleogeography, most of the alignment directions did not show distinctive differences. This supports the interpreted eolian-dominated depositional environment, where sandstone elongation trends would not have been controlled by position relative to the shoreline as might be expected of tidal-channel or lagoonal deposits.

Three of the four data subsets show irregular trends of less correlation with distance, as expected. Only the seven data points for the subset that is oriented northwest-southeast, parallel to depositional strike (i.e., parallel to the paleoshoreline) do not show a trend where correlation percentages drop off with distance, suggesting instead an implausible trend of higher correlation with greater distance. This may be due to spurious correlations at greater interwell distances as suggested above; it is more likely these are simply similar depositional environments and not laterally continuous beds.

In fact, without this data subset, the remaining 14 data points show a more definitive and steeper trend of decreasing correlation with distance between the well pairs (Figure 27b), suggesting that 50% of the sandy intervals may not extend laterally for more than about 1700 ft (518 m).

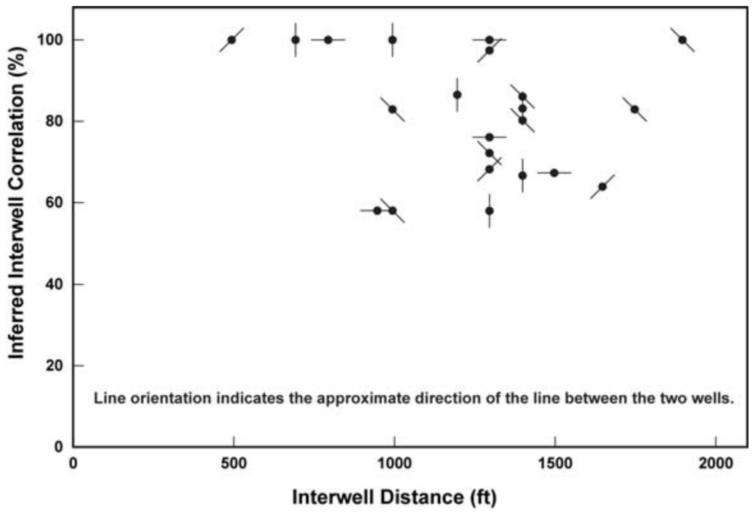

Figure 27a: Chart of the distance between wells versus the percentage of sandy packages that correlate between two wells for each of 21 well pairs. The correlation percentage decreases irregularly with distance, suggesting limits to the lateral extents of the sandy zones. The approximate orientation of the line between the two wells for each pair is indicated by the orientation of the slash through the data point ("north" is up).

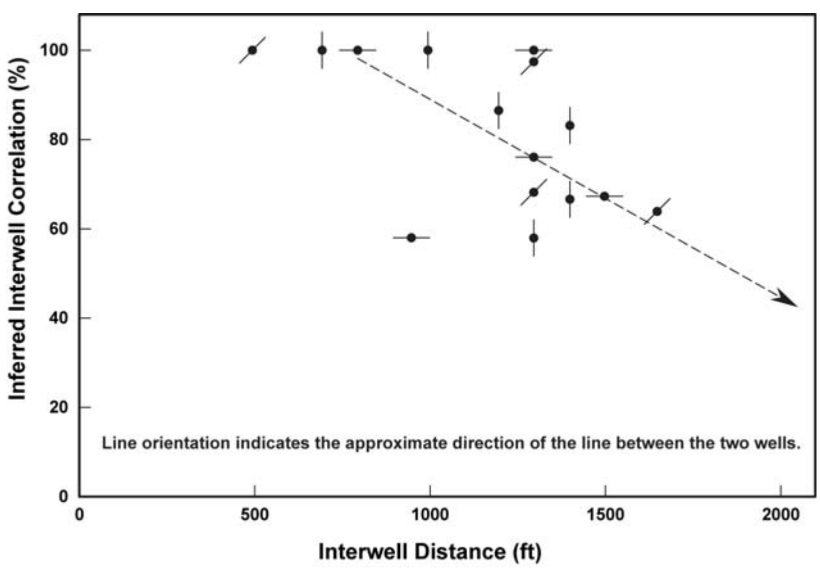

Figure 27b: The restricted data set of those fifteen well pairs having all orientations *except* northwest-southeast, showing better alignment of the data into a trend of decreasing correlation with increasing interwell distance. The dashed line is an estimated best-fit trend to the data points.

Reservoir Continuity and the Apparent Ponding of CO_2

The pre- and post-injection 3-D seismic results suggest that a bubble of CO_2 ponded at the base of the injection well (Figure 28). This, plus the higher than-expected-injection pressure (which necessitated an injection rate of only 40 tons per day rather than the calculated potential rate of 200 tons per day), suggests that the individual component beds of the Shattuck reservoir sandstones are not well interconnected, either laterally or vertically, and that even the compound sandstone beds are not laterally extensive.

The data on lateral continuity and interwell connectivity presented here suggest that fully half of even the compound sandstones extend laterally no farther than a few thousand feet. The radius of the mapped irregular CO_2 bubble is less than 1000 ft (305 m). The correlation of sandstones from the injection well to the five immediately adjacent wells are among the poorer correlations in the area, suggesting that the sandstones are more limited in lateral extent in this vicinity, possibly explaining this apparently restricted bubble of injected CO_2.

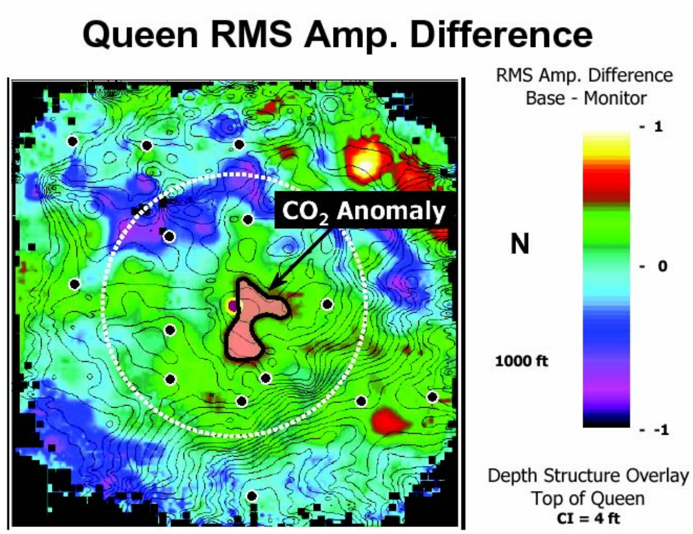

Figure 28: Three-dimensional seismic data showing the structure-contour map based on seismic data (black lines: compare to Figure 20a) and the interpreted CO_2 anomaly location based on root mean squared (RMS) analysis of the data. The Stivason Federal #4 injection well is the purple dot at the left margin of the CO_2 anomaly, and the Stivason Federal #5 observation/monitoring well is the first well to the east of the anomaly (north is up). Figure from Bob Benson, Colorado School of Mines.

A consideration is that the CO_2 bubble portrayed on the seismic map is two dimensional, whereas three and four separate, stacked, sandstone packages were perforated and presumably accepted the injected CO_2 in three dimensions. The seismic data do not have enough resolution to show CO_2 anomalies in each of the four injected reservoirs, therefore the seismic map shows the composite seismic response from the four zones, each in themselves being composed of smaller sand bodies, and each of which presumably has different lateral dimensions just as each has a different thickness.

The seismic anomaly may only portray the zone of maximum signal, where CO_2 is present in most or all four of the reservoirs. Individually, the four reservoirs probably extend further in different directions than the anomaly suggests. However, the observed high injection-pressure data argue that the reservoir extents are in fact limited, and that only a relatively small reservoir volume accepted CO_2.

None of the available data suggest that the reservoirs are limited structurally, but faults are not uncommon in the Permian basin and neither do the data rule out this possibility. In fact, the structure of the West Pearl Queen area is not well known: the seismically-derived structure map suggests a distinctly different structural configuration of the strata from the map constructed from well-log data (compare Figure 20a with Figure 28). Faults with vertical offsets of less than about 50 ft (15 m) would not be visible on the seismic data, yet a fault with only 10 ft (3 m) of throw would completely truncate most of the Shattuck reservoirs. A wrench fault would also truncate reservoirs but would have no vertical offset and thus even less seismic expression, nor would it show on a structure map based on well logs regardless of the magnitude of offset.

A fault would vitiate the reservoir-continuity estimations based on well data developed here, since it would truncate all reservoirs that it cuts. A small north-south fault located just west of the injection well would plausibly explain the asymmetric distribution of the anomaly, which is present only east of the injection well rather than radially symmetric around it, and truncated reservoirs would explain high injection pressures.

To date, no material-balance calculations have been carried out to test whether the area and volume of the mapped CO_2 anomaly are compatible with the injected gas volume and available reservoir volume. Another potentially useful approach would be to see if production and injection data support reservoir-engineering calculations that might indicate whether the reservoirs have apparent boundaries (faulted or otherwise) based on changes in the slope of draw-down and buildup curves.

A final consideration is that a small anomaly was present in the vicinity of the inferred CO_2 injection anomaly in the pre-injection seismic data. The significance of this anomaly, and of its coincidence with the inferred injection anomaly, has not been addressed.

Perforation Limitations on Fluid Connections between Wells

As noted above, only four of the five reservoir-quality Shattuck sandstones penetrated by the Stivason Federal #4 injection well were perforated. The perforated intervals range from three to eight feet thick, correlative to the thicknesses of the associated sandy-zone reservoir packages. A correlation of sandstone packages between the injection and observation wells (Figure 29) suggests that the upper perforated reservoir in the injection well may correlate to a much thinner sandstone in the observation well, but even if it does, it was not perforated in the observation well. It is limited in lateral extent, and the lack of perforations in the observation well precludes fluid transfer between wells in this zone.

The middle two perforated zones in the injection well may correlate to a single perforated sandstone in the observation well, i.e., either this zone has split and become two zones somewhere between the two wells, or there are three different reservoirs: two in one well and one in the other. The zones are probably poorly connected between the wells due to this sedimentary complexity.

Only the lowest sandstone package, immediately above the Queen Dolomite, has both apparently good correlation between the two wells and perforations in each of them. This six- to seven-foot thick zone would be the most likely to be continuous and to thus have the capability to conduct fluid between the wells.

Thus, only a third of the perforations, and thus probably only a third of the injected CO_2, went into a reservoir that is arguably contiguous between the observation and injection wells. The $CO_2$was injected at pressures that were purposefully maintained below the formation fracture gradient, thus the CO_2should have stayed in the injected reservoirs. It should not have been able to migrate vertically into the overlying reservoir that was perforated in the observation well.

Gasses from the production stream of the nearby Stivason Federal #5 well were monitored for composition, anticipating the breakthrough of CO_2, but none was observed until approximately three years after injection even though the well is only a quarter-mile to the east. Moreover, no changes in oil production that might be attributable to CO_2 injection were observed in this well during that time, also suggesting limited migration of CO_2 between injection and observation well, and therefore that interwell conductivity and continuity are not ideal even in the most promising zone.

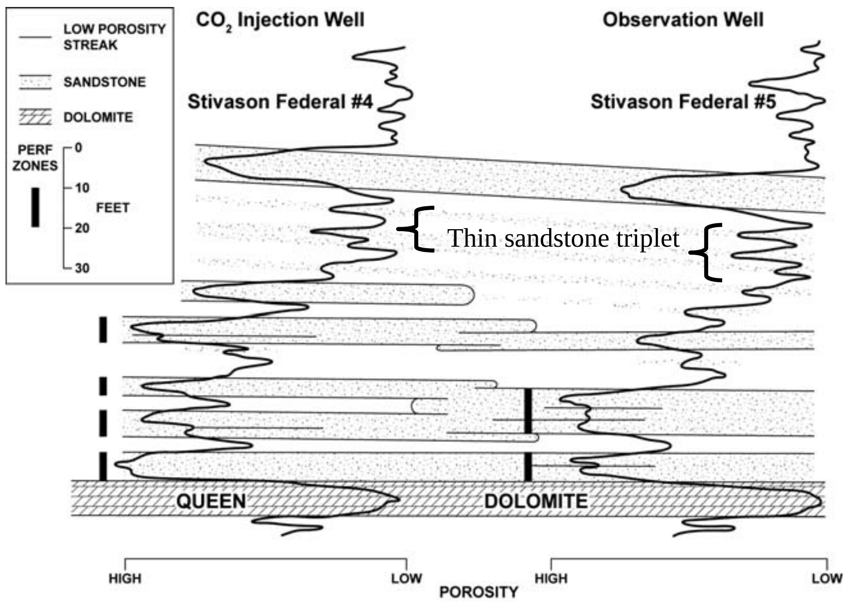

Figure 29: Interpreted correlations and continuity of Shattuck sandstones between one well pair: the Stivason Federal #4 (injection well), and the Stivason Federal #5 (observation/monitoring well) located approximately a quarter mile (0.4 km) to the east. Correlations of the non-reservoir sandstones in the upper part of the section are better, probably recording a shift to a more marine depositional environment. The Shattuck section is seven feet thicker in the injection well as a result of more subsidence and sedimentary accommodation space in this area.

Upper Shattuck Interval

The upper half of the Shattuck interval is predominantly fine grained and has low porosity. It contains thinner, individual sandstones, which, in the absence of core, cannot be definitively assigned to depositional environments. A distinctive triplet of thin sandstones in this upper interval (Figure 29) appears to extend laterally between most wells in the study area, but they are not thick enough to be significant reservoirs and were not perforated. The thicker, uppermost sandstone that caps the Shattuck interval also correlates between wells, blanketing the area, probably as a result of rising sea level.

Vertical Conductivity between Beds

Core data and the geophysical porosity logs suggest that vertical conductivity was interrupted by thin, finer-grained, low-porosity zones that separate the component beds within sandy zones, as well as by the thicker low-porosity zones that are interbedded between those zones. Minor inflections of the geophysical log porosity traces across the overall sandy intervals record these low-porosity zones within the reservoirs.

Cores suggest that the low-porosity zones are commonly less than half a foot thick, thus the geophysical-log trace does not have time to record the appropriate low-porosity indication during the brief sensor passage time across these intervals while recording the logs. Nevertheless, they are significant baffles to vertical permeability within the system. Porosity and permeability data taken from core plugs of the finer-grained, non-reservoir intervals in the Stivason Federal #1 well (Figure 30) demonstrate that permeabilities in the non–reservoir intervals are too low to allow ready vertical communication between reservoirs. The lack of ready communication of CO_2 vertically between those reservoirs injected into in the Stivason Federal #4 well and the different reservoirs perforated in the nearby Stivason Federal #5 observation well supports the inference that vertical fluid communication was limited within and between these reservoirs.

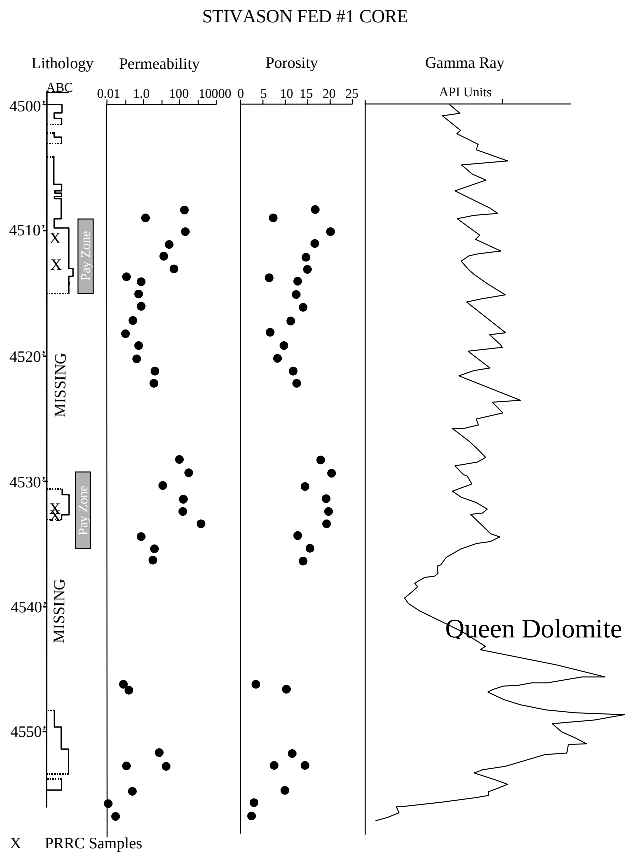

Figure 30: Porosity and permeability measurements from the Stivason Federal #1 core ("SF1" on previous figures) show that permeability drops below a millidarcy (and probably considerably less under in situ conditions of water saturation and stress) in the finer-grained intervals between reservoir sandstones, limiting vertical permeability within and across the reservoirs. Only two sandy packages had sufficient quality to be deemed "pay" zones by the operator in this well, even though it is only 1000 ft (305 m) southeast of the Stivason Federal #4 injection well where four sandy intervals had enough reservoir potential to have been perforated by the operator. This core extends below the Queen Dolomite, which is indicated by the low gamma-ray trace at about 4535-4544 ft (1382.2-1385.0 m). The high porosity/high permeability zone below the Queen Dolomite is irrelevant to the CO_2 injection since it was not within the area isolated by packers during injection. A significant percentage of this core had been removed for sampling, study, and souvenirs (the "missing" intervals).

The pores in the finer-grained beds between the reservoir sandstones are small, and they are commonly filled with cement, resulting in low permeabilities. Unless natural fractures exist to connect the reservoirs across the fine-grained intervals (and none have yet been observed in the limited core even though the outcrops are extensively fractured), fluids such as oil and/or CO_2 would not have ready communication among or between the different Shattuck sandstones.

CONCLUSIONS

The higher than-expected-injection pressure (which necessitated an injection rate of only 40 tons per day rather than the calculated potential rate of 200 tons per day), the 3-D seismic results which indicate a bubble of CO_2 ponded near the injection well, suggest that the individual component beds of the Shattuck reservoir sandstones are not well interconnected, either laterally or vertically, and that even the compound sandstone beds are not laterally extensive. This work analyzed the lateral continuity of the reservoir sandstones utilizing outcrop and subsurface data.

The observations on heterogeneities and the measurements of the lateral extents of reservoir-type sandstones in outcrop are compatible with and corroborate the inferences on limited reservoir dimensions made from subsurface data at the West Pearl Queen field. Sandstone outcrops in the area of Rocky Arroyo were deposited in eolian and shallow lagoonal environments. Heterogeneities such as facies changes, local bed thickenings, intraclast conglomerates, channels, and thrust faults interrupt lateral continuity of bedding and would effect the distribution of CO_2. Measured sandstone beds have an average minimum extent of 700 ft (213 m), but actual average extent is probably significantly more, on the order of 1500 ft (457 m).

Although the sandstone reservoirs of the Shattuck member occur in distinct zones and although they superficially appear to correlate between wells, they are probably not uniform, vertically-stacked, successive layers of laterally-extensive sandstone, and they are probably not contiguous between wells except at the closest well spacings. The maximum interpreted lateral extent of the sandy zones along the north-south cross section is 9000 ft (2740 m), but the lateral dimensions of most of these composite reservoirs were probably considerably less, and the larger inferred dimensions may be the result of apparent but spurious correlations.

Well-pair correlation data suggest that at least half of the composite sandstone reservoirs have lateral dimensions of less than 1700 to 2500 ft (520 to 760 m), depending on which data set is being used. Permeability drops to less than a millidarcy between reservoirs and at finer-grained sedimentary breaks within reservoirs, limiting vertical continuity within and between reservoirs. Limited reservoir dimensions and internal low-permeability baffles may explain the low CO_2 injection rates, the higher than expected injection pressures, the apparently small seismic anomaly related to CO_2 injection, and the observed lag in interwell communication.

The methods utilized in this paper to assess the lateral connectivity of reservoir rocks and to capture reservoir heterogeneities are applicable to other geologic sites and could provide a more thorough analysis of a reservoir before CO_2 injection is initiated.

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